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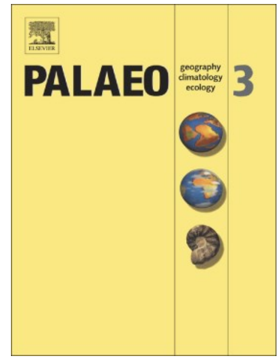

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Abstract

The Paraná Basin, the largest basin in South America, received glacially derived sediments during the Late Palaeozoic Ice Age (LPIA) of the Gondwana supercontinent. Despite the importance of this basin for understanding the continental development of the Gondwana glaciation, and the fact that ca. 95% of this basin is not exposed at the surface, few attempts have been made to connect the exposed glacial strata to the subsurface record. In this paper, exposures of glacial cycles in the Upper Itararé Group in Santa Catarina State, southern Brazil, are analyzed, locally correlated and then linked to the three major glacial cycles previously described from subsurface studies along the basin. Together study areas (Doutor Pedrinho and Vidal Ramos) record five, partially comparable shorter glacial subcycles (relative to the major glacial cycles). These series comprise coarse-grained subaqueous outwash deposits, turbidite sand sheets, marine shales, and diamictites, the latter mostly derived from delta slope failure and ensuing resedimentation. In addition to sedimentological and genetic stratigraphic description and analysis, preliminary age determination based on the palynological content is also presented. Besides, a regional correlation of the described succession to the subsurface record is proposed based on well logs and core information. All the palynomorph associations identified from the exposed successions, which represent the upper third part of the Itararé Group, are related to the Subzone *Protohaploxypinus goraiensis*, base of the *Vittatina costabilis* Zone. This zone and correlated ones along the Gondwana are considered Early Permian in age. However, a first isotopic age recently obtained for the upper Itararé Group and published elsewhere is considered within a regional stratigraphic framework once it leads to new insights in terms of the LPIA time span recorded in the Paraná Basin.

Keywords: Itararé Group, sequence stratigraphy, biostratigraphy, palynology.

1. Introduction

The Late Palaeozoic Ice Age (LPIA) represents the longest glacial interval recorded in the Phanerozoic (Veevers and Powel, 1987; Frakes *et al.*, 1992). It comprises diachronous episodes of glacial and non-glacial conditions recorded across the Gondwana supercontinent (Eyles *et al.,* 1993; López-Gamundí, 1997; Isbell *et al.*, 2003; Fielding *et al.*, 2008; Gulbranson *et al.*, 2010). In South America, the LPIA is reported from several basins, but the largest one recording such glacial evidence is the intracratonic Paraná Basin. According to several authors, in this basin the LPIA is recorded in the Itararé Group, which comprises widespread proglacial and rare subglacial deposits (Rocha-Campos 1967; Schneider *et al.*, 1974; Milani, 1997; Milani *et al.*, 2007; Rocha-Campos *et al.*, 2008; d´Avila, 2009; Vesely *et al.*, 2015; Aquino *et al.*, 2016; Fallgatter and Paim, 2017). Most of the existing studies of the LPIA in South America indicate an important difference in deposition of glacial deposits between the west and the east: whereas in the western side, glacial strata range from Mississippian to Pennsylvanian, based on both palynology and radiometric dating (Gulbranson *et al.,* 2010, Césari *et al.,* 2011), in Brazil glacial and proglacial beds have systematically been ascribed from Pennsylvanian to Early Cisuralian, but only based on palynological and other palaeontological data (Holz *et al.,* 2008, Neves *et al.*, 2014; Taboada *et al.*, 2016). This supposed time lag between the two areas has biased regional and even global correlations, and resulting palaeogeographical reconstructions. Only lately, the first radiometric dating of tuffites in the Itararé strata (Cagliari *et al.,* 2016) highlights the need for more radiometric dating of this unit, and a proper review of the existence or not of Permian glacial strata in the Paraná Basin.

Eyles *et al.* (1993) debated climate as the sole cause for the thick glacial record of the Itararé Group, as accumulation and preservation of glacio-marine successions are only possible under steady, tectonically controlled subsidence. Deposition within glaciated intracratonic basins involves a complex interplay between fluctuations in ice volume and resulting glacio-eustatic changes, glacio-isostasy, changes in sedimentary input, and tectonism. However, although subsidence has controlled preservation, climate was the main control on deposition of the Itararé Group due to its close association with ice advance and retreat, and resulting glacio-eustatic and glacio- isostatic processes (Canuto *et al.,* 1997, 2001).

The Itararé Group records at least three large-scale, fining-upward cycles ascribed to three long-term glacial cycles. These cycles are represented in both subsurface and outcrops and despite equivalents in terms of their stratigraphy, they receive different nomenclatures. Based on outcrop sections along the eastern margin of the basin, Schneider *et al*. (1974) divided the Itararé Group into the Campo do Tenente, Mafra and Rio do Sul formations. Later, França and Potter (1988) based on subsurface data divided it into Lagoa Azul, Campo Mourão and Taciba formations (Cycle I, II, and II in this work). According to these authors, the fining-upward nature of each formation reflects a cycle of glacier advance (mostly non-depositional) and retreat (mainly depositional and transgressive). Therefore, their boundaries are unconformities and they correspond to depositional sequences dominated by deglacial facies represented by diamictites, sandstones, and mudstones with dropstones (França and Potter, 1991; Eyles *et al.*, 1993; Santos *et al.*, 1996; Vesely and Assine, 2006; Rocha-Campos *et al.*, 2008; d´Avila, 2009).

These glacial cycles include three main marine maximum flooding surfaces recorded by the Roncador, Lontras and Passinho shales (of the Lagoa Azul, Campo

Mourão and Taciba formations respectively), which are well-known basin-scale stratigraphic markers.

Besides these major glacial episodes, some authors have also described regional scale, but higher-frequency glacial/deglacial cycles in Paraná and Santa Catarina states (Canuto *et al.*, 2001, Vesely and Assine, 2006; d´Avila, 2009; Vesely *et al.*, 2015, Fallgatter and Paim, 2017). The exposures around Doutor Pedrinho and Vidal Ramos provide good examples of deglacial deposits, mainly exposed in caves and waterfalls. They include thick packages of conglomerates and sandstones, interpreted as subaqueous outwash deposits (e.g. d´Avila, 2009; Aquino *et al.*, 2016) and sandy turbidite systems (e.g. d'Ávila, 2009; Fallgatter, 2015) that can be traced for tens of km (Fallgatter, 2015), as well as thin-bedded sandstones, remobilized intervals, marine mudstones and black shales, all of them quite often including dropstones. These exposures also include good examples of primary features related to glacial advance, such as striated pavements and glaciotectonic structures.

This paper describes two hundreds of meters thick glacial-related successions exposed in the Santa Catarina State, along the eastern outcrop belt of the Paraná Basin, including the description and evaluation of their palynological content, and correlates these exposures to the subsurface record towards the Paraná Basin depocentre (Paraná State and São Paulo states) as well as to the south (Rio Grande do Sul State), where tuffites were recently found in the Itararé Group and dated (Cagliari et al., 2016). After the surface-subsurface correlation, a chronostratigraphic scheme including major glacial cycles and several shorter-term glacial subcycles is then proposed.

2. Geological setting

2.1 Regional setting

The Paraná Basin is a large intracratonic basin that covers about 1,600,000 km^2 of southern Brazil, southeastern Paraguay, northeastern Argentina and northern Uruguay (Fig. 1). Its extension into Argentina is known as the Chaco-Paraná Basin, and records a distinct geological evolution (Zalán *et al.*, 1990). The basin displays an N-S trending oval geometry. Its western limit coincides with the N-S trending Asunción Arch whereas its northern limit is related to the NW-SE oriented Goiania/Alto Parnaíba Arch. Its eastern flank, where the study areas are situated, was deeply affected by the opening of the South Atlantic and subsequent evolution of the South American margin (Milani and Zalán, 1999).

The most accepted mechanism for basin initiation is oblique rifting due to extensional reactivation of basement structures (Milani, 1997), followed by a long- lasting sag. The basin shows a long history of sedimentation from Late Ordovician to Late Cretaceous (Milani *et al.*, 1994), which is recorded in six second-order sequences (Rio Ivaí, Paraná, Gondwana I, II, III and Bauru supersequences) bounded by inter- regional unconformities (Milani, 1997). The Gondwana I Supersequence records the Late Carboniferous to Early Triassic sedimentation that took place during the northward migration of the Gondwana supercontinent. The lower deposits of the Gondwana I Supersequence (Itararé Group) record the melting of a polar ice-sheet, with sedimentation largely influenced by resedimentation processes, and ensuing mass and sediment gravity flows in a general proglacial setting.

2.2 Local setting

The study areas (Doutor Pedrinho and Vidal Ramos) are located at the eastern border of the Paraná Basin, in the central to northern part of Santa Catarina State (Fig. 1). They include outcrops of the Campo Mourão and Taciba formations (França and Potter, 1988) of the Itararé Group in the study areas. The uppermost part of the Campo

Mourão Formation comprises the Lontras Shale (Fig.2), a basin-scale stratigraphic marker related to a maximum marine flooding (França and Potter 1988). This shale unit records the appearance of glossopterids followed by ferns (Iannuzzi 2013), and the incoming of new striate and polyplicate pollen grains such as *Illinites* and *Vittatina* (Souza, 2006). It also includes assemblages of marine fossils, such as brachiopods, bivalves, and conodonts (Rocha-Campos and Rösler 1978; Simões *et al*., 2012; Neves *et al*., 2014; Wilner *et al*., 2016). This mud-rich interval is here used as a datum to correlate the sedimentary succession of both study areas. The Taciba Formation includes a lower, sandy member (Rio Segredo), an intermediate, diamictite-rich member (Chapéu do Sol) and an upper, siltstone-rich member (Rio do Sul). Sandstones of the Rio Segredo Member are massive or graded and interpreted as turbidites. The Chapéu do Sol Member consists of massive to crudely stratified diamictites interpreted as thin- bedded turbidites and rainout deposits (mudstones with ice-rafted debris) modified by resedimentation processes.

3. Material and methods

Outcrop description was based on conventional techniques of facies and facies association analysis, and interpreted in terms of sedimentary processes and depositional systems, respectively. About 250 outcrops were described and mapped in the Doutor Pedrinho municipality and surrounding areas. For facies descriptions and stratigraphic analysis, sedimentological logs were acquired at the 1: 250 scale (Fig. 3B). In Vidal Ramos, previously described outcrops (Puigdomenech *et al.*, 2014) were revisited. Geological mapping was carried out using a Trimble GPS to locate outcrops on satellite images, and the resulting geological map (Fig. 3A) was constructed using ArcGIS 10.2.2.

Mudstones from several intervals were sampled to perform biostratigraphic analysis based on spore-pollen associations. Among 41 samples from both areas, 29 were selected for maceration. About 10 to 20 g of each sample was fragmented to facilitate reaction with acids. Standard palynological techniques were applied to recover organic-walled microfossils (Quadros and Melo, 1987). Inorganic material was dissolved using HF (silicates) and HCl (carbonates). Fraction of organic matter in the 25-250 µm range was separated by sieving. Slides were analyzed in optical microscopes (up to 1000 X magnification) and are stored in the Laboratório de Palinologia Marleni Marques Toigo in the Universidade Federal do Rio Grande do Sul under the codes "MP-P". Palynological analysis comprised the taxonomic identification of guide species of spores and pollen grains according to the zonal schemes for the basin (Souza and Marques Toigo, 2005; Souza, 2006). In the Vidal Ramos area, palynological samples were located in a previous stratigraphic column (Puigdomenech *et al.*, 2014).

A second part of this study deals with the correlation of the short-term glacial cycles (or depositional sequences) observed in the outcrop to the large-scale glacial cycles of the Paraná Basin. Well logs used by França and Potter (1988), Vesely (2006) Souza (2006) and Cagliari et al. (2016), were revised and analyzed in detail to situate the studied succession in an N-S, basin-scale stratigraphic section.

Sequence stratigraphic concepts based on Van Wagoner *et al.* (1988) were adapted to interpret the sedimentary succession of the studied areas. Therefore, sequence boundaries (SB) and their correlative conformities (CC) are supposed to represent the end of base-level fall and here ascribed to maximum. Lowstand systems tracts (LST) were subdivided into two successive components (early LST or fan and late

LST or wedge) and represent low accommodation and high to moderate sediment supply rates taking place just after successive episodes of ice maximum ice advance. Transgressive system tracts are common and represent much larger accommodation than supply rates. Highstand (HST) and falling stage (FSST) systems were only identified in the lower part of the Doutor Pedrinho and upper portion of the Vidal Ramos successions, respectively. A second terminology used to name the systems tracts was one adapted from studies of glaciated basins (Boulton, 1990; Martini and Brookfield, 1995; França et al., 1996; Visser, 1997; Brookfield and Martini, 1999; Vesely, 2001; Vesely and Assine, 2004). In this scheme, the advance and retreat of glaciers is the most relevant factor for systems tracts definition (e.g. Visser, 1997; Brookfield and Martini, 1999). The term MTD (mass transport deposit) was used in the sense of Nardin *et al.* (1979) as a general term that refers to slumps, slides and debris/mud-flow deposits produced by submarine mass movements. Long-distance correlation and biostratigraphic dating are supported by palynology (Holz *et al.*, 2008, 2010) and elsewhere across Gondwana (Stephenson, 2008) using spore-pollen species.

4. Results

4. 1 Doutor Pedrinho area

Two of the major glacial cycles (II and III) previously identified in subsurface by França and Potter (1988), which are bounded by the Lontras Shale, were recognized in the study area and correspond to Campo Mourão (mid to upper part) and Taciba formations of the Itararé Group. The succession (Fig. 3B) is up to 350-m-thick and largely composed of mudstones, with or without dropstones, but also includes sandstones and both clast- and matrix-supported conglomerates. This package mostly records proglacial-marine deposition including ice-rafted debris (IRD); varve-like, fine-grained rhythmites; massive and varve-like black shales; thin-bedded and sandy turbidites; subaqueous outwash fan facies; and chaotic deposits derived from debris- and mass-flows. According to Aquino *et al.* (2016), the Itararé Group in this area can be subdivided into three depositional sequences, each one composed of glacially influenced, marine to delta deposits, and is unconformably overlain by the post-glacial Rio Bonito Formation. Each depositional sequence represents a glacial subcycle (S1, S2, and S3) recorded by deglacial facies deposited during ice retreat (Deglacial Systems Tract or DST) above a sequence boundary (SB). These basal surfaces are characterized by deformational or scour features related to glacial advance (Aquino *et al.*, 2016) and/or abrupt shift of facies caused by a relative sea level drop associated with a less expressive glacial advance (d'Ávila, 2009; Fallgatter, 2015).

4.1.1 Depositional Sequence 1 (Glacial Subcycle S1)

The lower boundary represents a major non-conformity on Precambrian basement rocks. This sequence boundary includes well-developed glacial striae and represents a subglacial scour surface (SB1). It is overlain by laminated, sometimes rippled siltstones and thin layers of mudstone (Figs. 4A, B) that grade upwards to black to grey, silty-muddy rhythmites (Fig. 4C). This fining-upward, fine-grained succession includes abundant outsized extra clasts (small pebbles and granules of igneous and metamorphic rocks). A thin bed of matrix-supported conglomerate occurs within these rhythmites. The outsized clasts of both intervals are supposed to represent dropstones due to their oversized nature and impact features at their basal contacts. The presence of dropstone-rich, current rippled siltstone intercalated with mudstones suggests subaqueous outwash flows influenced by ice rafted debris (IRD) and rainout deposits.

Above the basal, fining-upward interval rests on a sharp contact a massive, about 80-m-thick diamictite (Fig. 4D). It consists of a siltstone-rich matrix with dispersed, up to 1.5 m long, sub-angular to sub-rounded clasts derived from basement rocks. The massive nature of the diamictite, the occasional presence of folded bedding planes and the fine-grained nature of the matrix point to a debris-flow origin. The outsized extraclasts dispersed in the fine-grained matrix indicates resedimentation of ice-rafted debris. Therefore, this entire interval (DST1) represents a mass transport deposit (MTD) involving the down slope remobilization of proglacial siltstones with dropstones.

4.1.2 Depositional Sequence 2 (Glacial Subcycle S2)

This sequence lies on an irregular surface (SB2) scoured into the above- mentioned MTD (Fig. 4E). The uppermost part of the subjacent MTD display foliation as well as compressional and extensional faults interpreted by Aquino *et al.*, (2016) as glaciotectonic features associated with a second episode of glacial advance (Fig. 4F). Therefore, and like the previous sequence boundary, this one also records a glacial scour feature. The entire package (DST2) is up to 50-m-thick, fines upward and comprises conglomerates, sandstones, fine-grained rhythmites and black shales.

The basal, coarse-grained deposits include polymictic conglomerates and sandstones (Fig. 5A). The basal conglomerates are lenticular and related to the filling of large depressions scoured into the MTD (Fig. 5B). They can be chaotic, massive, normal graded or stratified. Some boulder-size clasts are faceted and striated (Fig. 5C). The following sandstones recorded in the middle and upper portions of the basal succession (Fig. 5A) are unconfined and rest either on the conglomerates or directly on the previous MTD (Aquino *et al.*, 2016). Sandstones (Fig. 5D) comprise massive, normal graded, plane-bedded, low-angle cross-bedded or ripple cross-laminated facies. Sandstone bodies are laterally extensive and organized in small-scale, fining-upward cycles. The intercalation of massive and stratified, very poorly sorted and mostly coarse-grained deposits, including striated and faceted boulders, suggests unsteady, high-energy discharge. This interpretation, and the position of the package between subaqueous deposits (Fig. 12) and above glacio-tectonic features is consistent with previous models that relate these coarse-grained facies to subaqueous outwash fans produced by high energy, fluctuating melting water discharge of retreating glaciers (d´Ávila, 2009; Aquino *et al.*, 2016).

Above an abrupt contact, fine-grained rhythmites followed by black shales overlie the basal, coarse-grained interval (Figs. 5E, 5F and 12). Rhythmites comprise alternations of tabular lamina of siltstone and mudstone arranged as mm-scale couplets. Up to 0.5 cm long, basement-derived outsized clasts are common in the muddy layers, and understood as dropstones. The succession ends with a relatively thick, fissile black shale (Fig. 5F). The fine-grained couplets with small, dispersed extraclasts (dropstones) represent the beginning of a marine flooding and resulting settling from fine-grained plumes in the distal portion of a glacio-marine setting. The succeeding black shale (Lontras Shale) records the widespread marine maximum flooding that bound the (major) glacial cycles II and III.

4.1.3 Depositional Sequence 3 (Glacial Subcycle S3)

A sharp contact between the Lontras Shale and an overlying sandstone package (Figs. 6A, B and 12) delineates the lower boundary of the third, about 150-m-thick deglacial succession (DST3). Distinct from the previous sequence boundaries, SB3 shows no direct evidence of ice advance and neither of subaerial exposure. Therefore, the abrupt shift of facies above it, with more proximal deposits resting directly above deeper water fine-grained strata, indicates a correlative conformity. This package includes at its base an up to 30-m-thick interval composed of massive or normal graded, fine- to very fine-grained sandstones intercalated with mudstones (Fig. 6C). Beds are mostly tabular and comprise massive, plane-bedded and/or ripple cross-laminated (Fig. 6D) sandstone with or without intervening mudstone. As before noticed (d'Ávila 2009; Fallgatter, 2015) these sandstones record either high or low density (massive or plane-bedded and ripple cross-laminated, respectively), short-lived turbidity currents and long-lived, flood-derived hyperpicnal flows related to retreating glaciers. These gravity driven deposits constitute an extensive sand sheet that covers a minimum area of 1,200 km^2 (30x40 km; Fallgatter 2015).

A 50-m-thick interval composed of thin-bedded, fine- to very fine-grained sandstone to mudstone couplets (up to 2-cm-thick) occurs above the sandstone-rich interval (Fig. 6E). Sandstones are normal graded and can be either massive or ripple cross-laminated (Fig. 6F). These thin couplets of sandstone to mudstone represent thin- bedded turbidites produced by bipartite turbidity currents.

An interval about 60-m-thick and composed of diamictites and slumped beds covers the thin-bedded turbidites. It includes cm-scale, folded sandstone beds, sandstone blocks up to 5 meters across, and basement-affinity pebbles to boulders size clasts dispersed in a silty matrix (Figs. 6G, 6H). There is a clear genetic relationship between slumped beds and diamictites, hence this unit is interpreted as a mass transport deposit (MTD). Shallow water sedimentary features (e.g. wave ripples) in the larger sandstone blocks suggest remobilization of delta front facies into a deeper water setting, as previously suggested for this area (d´Ávila 2009) and elsewhere during the Itararé Group deposition (e.g. Suss *et al.*, 2014). At last, the post-glacial Rio Bonito Formation, resting above a subaerial unconformity (SB6 – Fig. 12) and comprising mostly coastal deposits and the largest coal measures of Brazil, overlies the DST3.

4. 2 Vidal Ramos area

Based on the correlation of both study areas (Fig. 12), deglacial systems tracts, depositional sequences, sequences boundaries and glacial subcycles are labeled either as equivalent or successive units relative to the Dr. Pedrinho area in order to build a composite succession. According to Puigdomenech *et al.* (2014), the succession exposed around Vidal Ramos represents the uppermost portion of the Campo Mourão Formation (Lontras Shale) and a more complete record (relative to the previous area) of the Taciba Formation. It fills an irregular topography carved by glacial processes into Paleoproterozoic schists and marbles of the Brusque Metamorphic Complex (Fallgatter and Paim, 2017). Four depositional sequences ascribed to four glacial subcycles (S2, S3, S4 and S5) were discriminated with sedimentation (deglacial systems tracts) taking place during ice retreat and sequence boundaries (SB) associated with episodes of ice advance. The description and interpretation of the main facies associations are also based on Puigdomenech *et al.* (2014), but here ascribed to four successive DST, each one equivalent to a depositional sequence.

4.2.1 Depositional Sequence 2 (Glacial Subcycle S2)

This basal, up to 20-m-thick interval corresponds to the upper part of the DST2, the Lontras Shale. It comprises black shales and mm-scale, graded couplets of dark grey siltstone and black claystone. This interval (DST2) records deep marine, proglacial sedimentation derived from distal, low concentration turbidity plumes and hemi-pelagic sediments associated with dropstones. According to Fallgatter and Paim (2017), the Lontras Shale and the succeeding deposits are confined to the ice-carved, NNW aligned, and striated (Fig. 7A) Alfredo Wagner Palaeovalley. Therefore, SB2 corresponds to a non-conformity, distinctly from the Doutor Pedrinho area where it records a glacial scour feature within the Itararé Group. This updip change on the SB2 nature reflects the continuous southward onlap of the Itararé Group onto basement rocks.

4.2.2 Depositional Sequence 3 (Glacial Subcycle S3)

Up to 130-m-thick, this interval (DST3) includes sandy turbidites, mass transport deposits, thin-bedded turbidites and black shales. The basal, up to 30-m-thick sandy turbidites rest abruptly on the Lontras Shale and are also confined to the glacial palaeovalley (Fig. 7B). Like in Doutor Pedrinho, coarser-grained, more proximal sandy turbidites resting right above deep water shale also suggest a correlative conformity as the SB3. These sandstones represent deposition during early deglaciation stages, and resulting high rates of ice melt discharge and consequently high sediment input from calving glaciers into the flooded valley. The following 100-m-thick package comprises thin-bedded turbidites that include two intervals of mass transport deposits (MTD). The thin-bedded turbidites represent a distal delta front to prodelta setting subject to occasional failure, and resulting slumped beds and ressedimented diamictites (Figs. 7C, D). The latter ones include pebble- to cobble-size extra-clasts interpreted as dropstones. Upwards, the succession becomes finer-grained, with rhythmites composed of 2 to 5 cm thick, usually massive or current-rippled sandstones intercalated with mudstones. A second, about 20-m-thick interval of black shales defines the uppermost part of the DST3.

4.2.3 Depositional Sequence 4 (Glacial Subcycle S4)

This unit (DST4) is similar to the previous one. Another interval of sandy turbidites (20-m-thick) rests abruptly on the above-mentioned black shales (Fig. 7E) and characterizes an additional correlative conformity (SB4). It is overlain by about 20 m of fine- to very fine-grained sandstone to mudstone couplets interpreted as thin-bedded turbidites. The latter presents an overall fining-upward trend and once more finishes with dark grey mudstones.

4.2.4 Depositional Sequence 5 (Glacial Subcycle S5)

Like all previous sequences, an abrupt boundary also delineates its basal contact, as dark grey mudstones of the previous sequence are sharply overlain by a sandstone-prone interval (DST5). Likely, it also represents a correlative conformity as shallower sandy facies (see description below) rest right above deeper, fine-grained deposits with no evidence of subaerial exposure. However, and distinctly from the previous depositional sequences, sandstone beds are arranged within coarsening- and thickening- upward parasequences. Parasequences are composed of mudstones and predominant very fine- to fine-grained sandstones (Fig. 7F) and arranged in a progradational, up to 50-m-thick parasequences set. Sandstone beds are laterally extensive, up to 2-m-thick, and almost entirely accumulated through the climbing of current ripple (Fig. 7G). This evidence indicates high rates of sand fallout, here associated with long-lived, steady hyperpycnal flows related to friction-dominated effluents on a proximal delta front setting.

4.3 Palynology

Nine samples from Doutor Pedrinho and three from Vidal Ramos, revealed well-preserved and diverse palynological assemblages. The remaining 17 samples display a poor palynological content (scarce and indeterminate palynomorphs, semi-destroyed phytoclasts and amorphous organic matter) or are barren. The complete list of the palynomorphs is presented in Table 1, whereas figures 8 and 9 show the stratigraphic distribution of taxa for each area. Photomicrographs of selected palynomorphs are presented in Figure 10, including the most important index fossil. Terrestrial spores and pollen grains are dominant in productive samples, followed by few specimens of Chlorophyta algae, related to Chlorophyceae (*Botryococcus braunii*) and Prasinophycean (*Deusilites tenuistriatus*, *Leiosphaeridia* spp. and *Tasmanites* spp.).

Among the continental flora representatives, pollen grains are more common, especially radial (mainly *Cannanoropollis*) and bilateral (*Caheniasaccites*, *Potonieisporites*) monosaccates, bisaccate taeniate (*Protohaploxypinus*, *Illinites*), followed by polyplicate (*Vittatina*) and other praecolpate and taeniate species. Spores are less frequent, highlighting species of smooth (*Leiotriletes*, *Punctatisporites*) and cingulizonate (*Vallatisporites*, *Cristatisporites*) genera. Diverse and abundant associations are especially verified in some samples from Doutor Pedrinho (DPR 100, 108 and 153) as well as in the three productive samples from Vidal Ramos (VRRO 35, VR-IM-03 and VRRO 28).

5. Glacial-deglacial cycles and sequence stratigraphy

The Lontras Shale was used as marker for correlating the study areas (Fig. 12). Therefore, five glacial subcycles were identified, two of them (S1 and S2) associated with Glacial Cycle II and three of them (S3, S4 and S5) with Glacial Cycle III. All subcycles are bounded by surfaces (sequence boundaries) associated with episodes of ice advance (Glacial Advance Systems Tracts or GA) and resulting relative sea-level fall. However, these sequence boundaries show no piece of evidence of subaerial exposure, *i.e.*, represent subaqueous, erosive (ice-contact surfaces such as SB1 and SB2) or non-erosive (correlative conformities such as SB3, SB4 and SB5). The only exception is the subaerial unconformity that delineates the boundary between proglacial and post-glacial strata of the Taciba and Rio Bonito formations, respectively. SB are highlighted by abrupt shifts of facies related to the deposition of the basal, usually coarser-grained strata of the deglacial systems tract (DST) above usually finer-grained beds of the previous DST or depositional sequence.

All DST comprise proglacial, mostly marine deposits and represent cycles of ice retreat, and resulting relative sea-level rise. They include at their base distal (S1) to proximal (S2) subaqueous outwash deposits, sandy turbidites (S3 and S4) or delta front strata (S5).

Gravelly to sandy outwash deposits (S1 and S2) grade upwards through mudstones to usually black shales. The entire fining- and thinning-upward packages were ascribed to transgressive systems tracts that culminate with maximum flooding surfaces (MFS1 and 2). No lowstand deposits were associated with the outwash facies as they show a clear transgressive trend. On the other hand, basal turbidites (S3 and S4) are aggradational and covered by thick packages of thin-bedded turbidites (tbt), often remobilized as slumps to debris-flows, deposited on a proglacial, unstable delta slope. Dark grey mudstones and lastly black shales related to maximum marine flooding rest above these heterolithic strata. Therefore, and in accordance with previous model (Puigdomenech *et al.,* 2014), sandy turbidites were associated with early lowstand stages, tbt packages with late, lowstand wedges and following black shales with maximum marine flooding (Fig. 12).

It is important to notice that the hyperpicnal nature of some turbidite beds as well as the presence of plant debris and drag marks, point out the existence of a subaerial outwash fluvial system during the deposition of the basal strata of the S3 and S4, hence indicating a more distant, continental ice-front relative to previous distal (DST1) and proximal (DST2) subaqueous outwash fans.

Differently from the previous cases, the DST 5 comprises the stacking of delta front sandstones right above deeper water, black shales of the previous sequence (MFS 4). This vertical succession indicates a relative sea-level drop, therefore a forced regression. Then, the delta front sandstones could be ascribed to either a lowstand wedge or falling-stage systems tract. As these rather proximal delta facies were later exposed to subaerial processes, and only afterwards covered by the coastal deposits of the post-glacial Rio Bonito Formation, it seems reasonable to assign them to one step of sea level still stand within an overall sea-level drop. The isostatic rebound caused by the removal of a large ice cap at end of the LPIA in this portion of the Gondwanaland is assumed as a possible cause for this widespread relative sea-level fall and consequent regional-scale unconformity that bounds the Itararé Group and Rio Bonito Formation.

Only one sub cycle records sedimentation above the MFS (Fig. 12). It is related to S1 where mudstone and shale related to a maximum flooding (MFS1) are overlain by an 80-m-thick interval of resedimented facies (MTD1), which is supposed to represent the complete failure of delta strata related to a highstand systems tract (HST1).

6. Age and correlation of the glacial cycles across the Paraná Basin

Marine invertebrate fossils, such as conodonts and foraminifers, are absent or very scarce in most of the Upper Paleozoic Gondwana basins, preventing an accurate age establishment founded on the international chronostratigraphic scale. Radiometric ages have been obtained from several stratigraphic levels in distinct regions of Gondwana (see Césari *et al.*, 2011). However, most of the data available for the Paraná Basin comes from tonstein layers recorded within coals and related strata of the postglacial Rio Bonito Formation. In this context, palynology has been the single biostratigraphic tool for dating the Pennsylvanian-Permian strata due to the abundance, diversity and widespread distribution of the spore-pollen assemblages. These organic- walled microfossils have furnished relative ages and supported short- and long-distance correlations (e.g., Milani *et al.*, 2007; Holz *et al.*, 2008, 2010).

Four palynozones have been recognized by Souza and Marques-Toigo (2005) and Souza (2006) in the Upper Paleozoic deposits of the Paraná Basin, in the following ascending stratigraphical order: *Ahrensisporites cristatus* (AcZ), *Crucisaccites monoletus* (CmZ), both related to the Middle to Upper Pennsylvanian, *Vittatina costabilis* (VcZ) and *Lueckisporites virkkiae* (LvZ) zones, of Early and Early to Middle Permian age, respectively. Figure 11 presents a summary of this palynological succession, including correlation between these palynozones and those previously established by Daemon and Quadros (1970) and Marques-Toigo (1988, 1991).

The studied areas revealed guide species of the Early Permian *Vittatina costabilis* Zone of Souza and Marques-Toigo (2005), such as *Converrucosisporites confluens*, *Illinites unicus*, *Vittatina costabilis*, *V. subsaccata*, *V. vittifera* and *Protohpaloxypinus goraiensis*. Besides, the quantitative features from the productive samples of both areas are in accordance with this interval zone, especially the basal *Protohaploxypinus goraiensis* Subzone, which is characterized by bilaterally and radially symmetrical monosaccate pollen grains, herein represented by several genera, such as *Cannanoropollis*, *Potonieisporites* and *Cahenisaccites*. The record of several species of *Vittatina* in these areas is very significant, given that the incoming of this genus in the palynological successions is considered a special datum throughout the basin, with correlative zones elsewhere in South America (see Azcuy *et al.*, 2007). The first appearance of this genus in the Paraná Basin is concomitant with the incoming of *Illinites unicus* and *Converrucosisporites confluens*, as recorded herein.

Similar palynological assemblages were also described from the upper Itararé Group in distinct areas of the Paraná Basin, such as in São Paulo (Souza and Callegari, 2004), Santa Catarina (Pons, 1976a, 1976b; Gandini *et al.*, 2007) and Rio Grande do Sul (e.g., Dias, 1993; Smaniotto *et al.*, 2006). Outside the Paraná Basin, this assemblage is comparable to several others described from Permian LPIA strata in Gondwana, such as in South America (Vergel, 1993; Beri *et al.*, 2012), Africa (Falcon, 1975; Stephenson, 2008), Oman and Saudi Arabia (Stephenson and Filatoff, 2000), Australia (Jones and Truswell, 1992), India (Lele and Makada, 1972) and Antarctica (Lindström, 1995).

The maximum flooding surfaces recorded in the three different formations reported by Franca and Potter (1988) and the time interval ascribed to each palynozone support the inferences about the duration of the three-long term glacial cycles recorded in the Paraná Basin. The Roncador Shale yields the palynological assemblage of *Ahrensisporites cristatus* Zone (AcZ) indicating that the sedimentation of the Lagoa Azul Formation (recognized in São Paulo and Paraná states) would have begun during the Early Pennsylvanian, maybe late Bashkirian (Souza and Marques-Toigo, 2005; Souza, 2006; Rocha-Campos *et al.*, 2008). Recently Vesely *et al.* (2015) suggested a late Bashkirian age based on the AcZ Biozone recorded at the Ventania-Ibaiti basal succession (Fig. 13). The base and middle part of the Campo Mourão Formation yields the palynological assemblage of *Crucisaccites monoletus* Zone (CmZ) suggesting a Moscovian -? Gzhelian age (Iannuzzi, 2013). The Lontras Shale, located in the upper part of Campo Mourão Formation, records the appearance of glossopterids followed by ferns, and incoming of several varieties of pollen grains, including the genus *Vittatina* (Souza, 2006; Iannuzzi, 2013). This silt- to mud-rich interval is a regional datum here used to correlate both surface and subsurface successions (Figs. 12, 13). Finally, the Passinho Shale, included in the upper part of the Taciba Formation, records the *Vittatina costabilis* Zone (Petri and Souza, 1993) that suggests an Early Permian age.

7. Discussion

According to the original proposal of the VcZ (Souza and Marques-Toigo, 2005), the palynological assemblages found in Doutor Pedrinho and Vidal Ramos successions are Early Permian in age. However, in view of the new radiometric data obtained by Stephenson (2008) and Cagliari *et al*. (2016) combined with our analysis and correlation of surface and subsurface data based in stratigraphy and biostratigraphy, an older Pennsylvanian age for the VcZ cannot be discounted.

Radiometric dating of different levels within the glaciogenic Itararé Group (323.6 ± 15 Ma and 356.9 ± 22 Ma, in Rocha-Campos, 2006) place this unit well in the Carboniferous, but their error is too large to consider them as good absolute ages. More recent radiometric dating (307±3.1 Ma) of tuffs found near the top of the Rio do Sul Formation (upper unit of the Itararé Group, largely equivalent to the Taciba Formation) in the Rio Grande do Sul State presented by Cagliari *et al.* (2016) re-enforces a Carboniferous age for most if not all Itararé Group (Figs.12 and 13). Figure 12 displays the correlation of the AC-72-RS (and recently dated level) with the Vidal Ramos succession (notice that correlation between the dated outcrop and the 8 km far AC-72- RS well is that indicated by Cagliari et al. 2016 based on field relations). And Figure 13 extends this correlation to a much broader, regional stratigraphic framework chiefly based on biostratigraphy and correlation of major maximum flooding surfaces. It is also important to notice (Fig. 13C) the southward onlap of the Itararé Group strata, with deposition of a much thicker column in the depocentre and progressively thinner and younger units southwards.

Although the palynological content of the deposits associated with the dated tuffite was not described yet to certify the presence of the *Vittatina costabilis* Zone, the regional correlation (Fig. 13) suggests that entire Itararé Group is actually confined to the Carboniferous, as previously proposed by Cagliari et al. (2016). This assumption implies in a conflict between the supposed VcZ age and radiometric data, as suggested by the biozones ages column in the left and tuffite age in the right of Figure 13B. Assuming the biostratigraphic age for the older biozones and the radiometric age for the top of the Itararé Group, this unit records a much smaller interval than previously supposed (Early Bashkirian to late Moscovian). Nevertheless, this hypothesis must be tested with a larger number of precise radiometric dating associated with palynological studies of the sampled sites.

Based on all the previous discussion, and data limitations, it is possible to assume that the entire glacial episode recorded in the Itararé Group lasted about 16 Myr and includes glacial cycles (about 4 to 6 Myr) that are roughly equivalent to the Lagoa Azul, Campo Mourão and Taciba Formations (Fig. 14).

Besides these long-term glacial cycles, and like what was here described, many authors have also proposed the occurrence of shorter glacial cycles (e.g. Canuto *et al.*, 2001; Vesely and Assine, 2006). Towards the Paraná Basin depocenter (western part of the São Paulo State), where the Itararé Group thickness reaches about 1,400 m, it is possible to recognize in the subsurface at least nine of these higher-frequency glacial cycles (Fig. 13). Canuto *et al.* (2001) distinguished seven 3rd-order depositional sequences based on the identification of fining- to coarsening-upward cycles in northern Santa Catarina and southern Paraná states. In northern Paraná State, Vesely and Assine (2004, 2006), divided the Itararé Group into five 3rd-order depositional sequences. Furthermore, our results in the Doutor Pedrinho and Vidal Ramos areas indicates within a single palynological biozone (VcZ) the record of five short-term glacial / deglacial cycles related to episodes of glacier advance and retreat. However, the time span of each cycle, and resulting hierarchy of the associated depositional sequence (3rd-order or high-frequency, orbital-driven glacial cycles), is a matter that still requires a larger amount of high quality radiometric data.

8. Conclusions

The exposed succession of both studied areas revealed guide species of the *Vittatina costabilis* Zone, which is usually assumed as ranging from late Pennsylvanian to early Cisuralian. However, the hypothesis of the Late Palaeozoic glaciation that affected the Paraná Basin have been confined to the Pennsylvanian is assumed based on the available radiometric data and the regional correlation of depositional sequences and glacial events. A proper evaluation of the palynological content at or nearby the dated interval must be perform to confirm the presence of the same sub-zone. And new radiometric data along the entire Itararé Group are necessary not just to the test the Carboniferous hypothesis, but also to refine the beginning of glaciation and duration of the shorter-scale glacial cycles.

Glacial subcycles recorded in the upper part of the Itararé Group exposed in Santa Catarina State were correlated to the glacial cycles known from subsurface studies. The Itararé Group in the study areas is represented by the Campo Mourão and Taciba formations. Five successive glacial subcycles, and their corresponding glacial advance (GA) and deglacial (DST) systems tracts, were identified. Along each glacial / deglacial cycle, erosion or non-deposition took place during ice advance whereas deposition mostly records ice retreat. The discrimination of five depositional sequences related to five successive, short-term glacial cycles within a single biozone (*Vittatina costabilis* Zone) encompasses only a small part of the Itararé Group (roughly its upper third), and indicates that the LPIA in the Paraná Basin may provide important clues to the duration of both long- and short-term glacial cycles as absolute ages become better constrained.

Prevalence of lowstand and transgressive systems tracts and abundance of gravity-driven facies suggest a long-term, lowstand setting for the LPIA succession, as expected during a long-lasting ice-house period. Deposition, mostly restricted to the deglacial episodes, records high rates of sediment input due to episodes of ice melting and retreat. Moreover, these high rates of sediment input seem to have been the main cause of the large amount of gravity-driven deposits that makes the Itararé Group very distinct to all other, younger and older units recorded in the Paraná Basin.

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Captions

Figure 1: Simplified geologic map of the Paraná Basin showing structural contours (basement depth) and the outcrop belt of each supersequence (after Milani *et al.,* 1994). The black box delineates the study area.

Figure 2: The Itararé Group subdivisions based on subsurface data according to França and Potter (1988).

Figure 3: Study area. A) Geological map of Doutor Pedrinho area (modified from d´Avila 2009). The Itararé Group is subdivided into three subcycles. B) Composite log of Doutor Pedrinho area. Subcycles 1 and 2 belong to the Campo Mourão Formation whereas the third subcycle corresponds to the Taciba Formation.

Figure 4: Sedimentary deposits of the deglacial system tract 1 (DST 1). A) Silty-muddy rhythmites (SMR); and muddy-silty rhythmites (MSR) with dropstones interpreted as ice rafted debris (IRD). B) About 25 cm wide granitic dropstone immersed in fine- grained deposit. Hammer for scale. C) About 15 m of reddish and black to grey shales and laminated mudstones (Fl). Person for scale. D) About 80-m-thick interval of resedimented diamictite (MTD). Person for scale; and synsedimentary E) shearing and F) faulting on top of the MTD produced during ice advance.

Figure 5. Sedimentary deposits of the deglacial system tract 2 (DST 2). A) Outwash conglomerates and sandstones. Person for scale. B) Ortho-conglomerate at the base of the DST 2. C) Detail of a faceted and striated outsized granitic clast found at the base of the DST2. Hammer for scale. D) Tabular beds of massive sandstones. Person for scale. E) mudstone/siltstone rhythmites; and f) black shales (Lontras Shale). Person for scale.

Figure 6: Sedimentary facies of the deglacial systems tract 3 (DST 3). A) Lontras Shale overlain by sandy turbidites. Person for scale. B) Sandy turbidites in the Doutor Pedrinho area resting above the Lontras Shale. C) Thick bedded turbidites including massive sandstones. Person for scale. D) Ripple cross-laminated sandstones intercalated with mudstones and siltstones. Hammer for scale. E) Thin bedded turbidites. F) Detail of thin bedded turbidites. G) Sandstone block within the MTD matrix. Note the rounded granitic dropstone beside the person for scale. H) Slumped and folded beds of a MTD. Hammer for scale.

Figure 7: Features and facies in the Vidal Ramos area. A) Striated Precambrian basement related to ice advance. B) The Lontras Shale at the base of the succession overlain by sandy turbidites. Person for scale. C) Slumped folds in the MTD. Person for scale. D) Proglacial diamictite with granitic dropstones enclosed in a muddy matrix. Hammer for scale. E) A second interval of black shales overlain by a second turbidite sand sheet; F) Prodelta sandstone facies above thin-bedded turbidites; and G) cross- and plane-bedded sandstone facies related to a delta front setting. Hammer for scale.

Figure 8. Palynostratigraphic data from the Doutor Pedrinho area: A) position of the samples along the simplified stratigraphic column (for additional geological information see legend of Fig. 4); B) Sampled levels and respective slides (under code "MP-P", relating to the slide collection of the Marleni Marques Toigo Palynology Lab.)

Figure 9: Palynostratigraphic data from the Vidal Ramos area: A) position of the samples along a simplified stratigraphic column (for additional geological information see legend of Fig. 13); B) Sampled levels and respective slides (under code "MP-P", relating to the slide collection of the Marleni Marques Toigo Palynology Lab.)

Figure 10. Photomicrographs of selected palynomorphs. A) *Converrucosisporites confluens* (Archangelsky and Gamerro) Playford and Dino 2002 (slide MP-P: 7718, coordinate England Finder D45); B) *Cannanoropollis mehtae* (Lele) Bose and Maheshwari 1968 (7699, L54); C) *Potonieisporites magnus* Lele and Karim 1971 (7719, X46); D) *Caheniasaccites flavatus* Bose and Kar emend. Azcuy and di Pasquo 2000 (7718, P28); E) *Protohaploxypinus goraiensis* (Potonié and Lele) Hart 1964 (7699, M40-2); F) *Marsupipollenites striatus* (Balme and Hennelly) Foster 1975 (7718, Y52); G) *Illinites unicus* Kosanke emend. Jansonius and Hills 1976 (9231, V38); H) Vittatina *costabilis* Wilson 1962 (7718, K51); I) *Vittatina vittifera* (Luber) Samoilovich 1953 (7719, O38-4); J) *Hamiapollenites* sp. (7718, M35); K) *Hamiapollenites fusiformis* Marques-Toigo emend. Archangelsky and Gamerro 1979 (7718, Y47); L) *Polarisaccites bilateralis* Ybert and Marques-Toigo 1971 (7541, H50-4). Scale bar corresponds to 20 μm.

Figure 11. Summary of the Pennsylvanian and Permian palynological succession of the Paraná Basin (geochronology is according to Cohen *et al.*, 2013).

Figure 12: Correlation, sequence stratigraphy (Van Wagoner *et al.*, 1988) and glacial-deglacial subcycles in the study areas. Adopted acronyms: SB (sequence boundary); MFS (Maximum Flooding Surface); FS (Flooding Surface); GA (Glacial Advance); DST (Deglacial System Tract); TST (Transgressive Systems Tract); HST (High Stand Systems Tract, FSST (Falling Stage System Tract); and LST (Lowstand Systems Tract), the latter subdivided into two successive components, the Early Lowstand Systems Tract (or Basin Floor Fan) and the Late Lowstand Systems Tract (or Lowstand Wedge).

Figure 13: Paraná Basin regional correlation. (A) Isopachs of the Itararé Group and location of the basin-scale regional- correlation charts (B and C). (B) Subsurface / surface higher resolution stratigraphic correlation chart including glacial cycles, the studied areas, well data information and biozones. Well cores described elsewhere: 2 PP 1 SP and 2 PN 1SP from França and Potter (1988) and Souza (2006); 2CS 1 PR, 1 RS1 PR and 1MB 1SC from França and Potter (1988), Vesely (2006) and AC-72-RS from Cagliari et al. (2016). The Ventania-Ibaiti surface section revisited from Vesely *et al.* (2006). (C) Basin-scale correlation chart, notice the thickness changes of the Itararé Group along the basin and the relatively thin and young record exposed in the studied areas relative to the entire Itararé Group and to the well logs record.

Figure 14: Stratigraphic scheme of the Parana Basin showing the long and short-term glacial cycles. Super cycle (Itararé Group), cycles (Lagoa Azul, Campo Mourão and Taciba Formations) and subcycles recorded at Doutor Pedrinho and Vidal Ramos outcrops (S1, S1, S3, and S4).

Table 1. Palynological content found in the Doutor Pedrinho and Vidal Ramos samples.

Figures

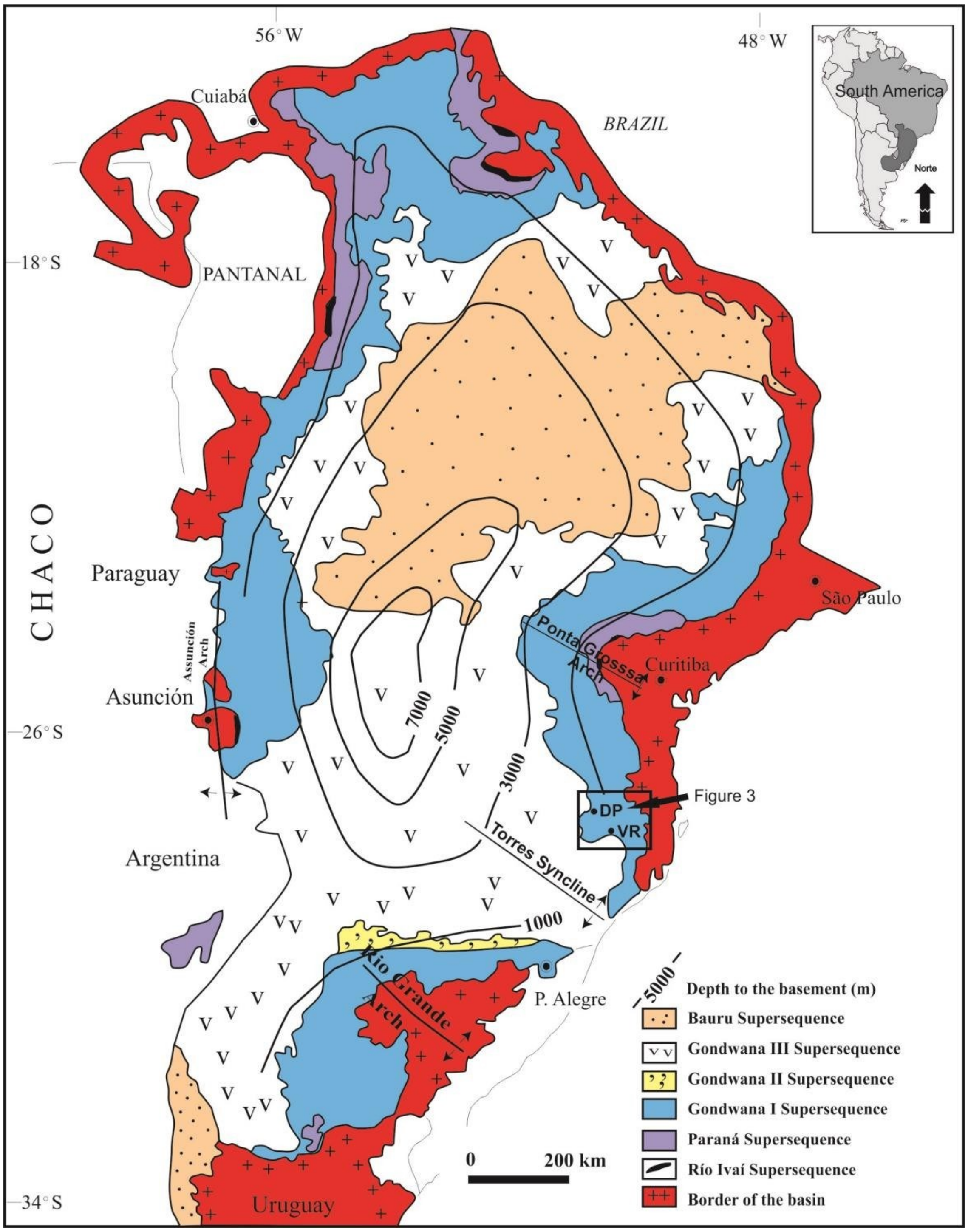


Figure 1

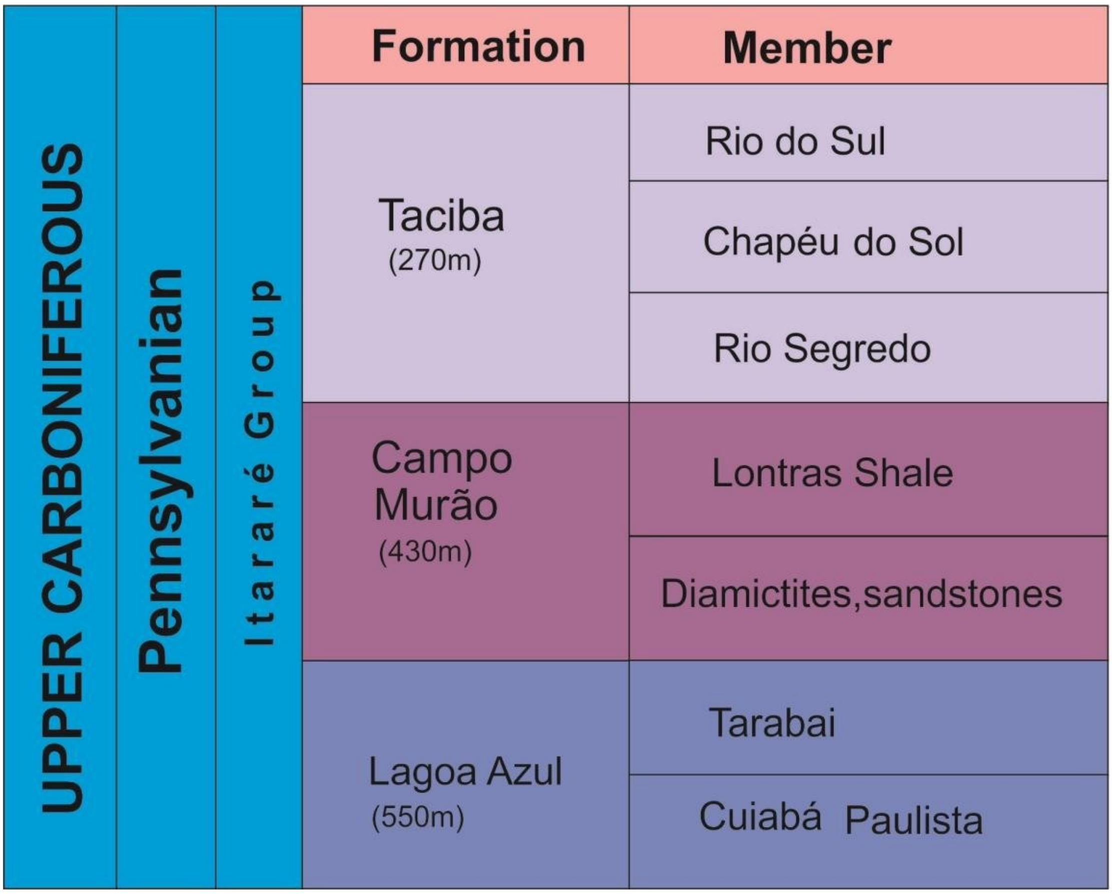

UPPER CARBONIFEROUS
Pennsylvanian
Itararé Group
Formation
Member
Taciba
(270m)
Rio do Sul
Chapéu do Sol
Rio Segredo
Campo Murão
(430m)
Lontras Shale
Diamictites,sandstones
Lagoa Azul
(550m)
Tarabai
Cuiabá Paulista

Figure 2

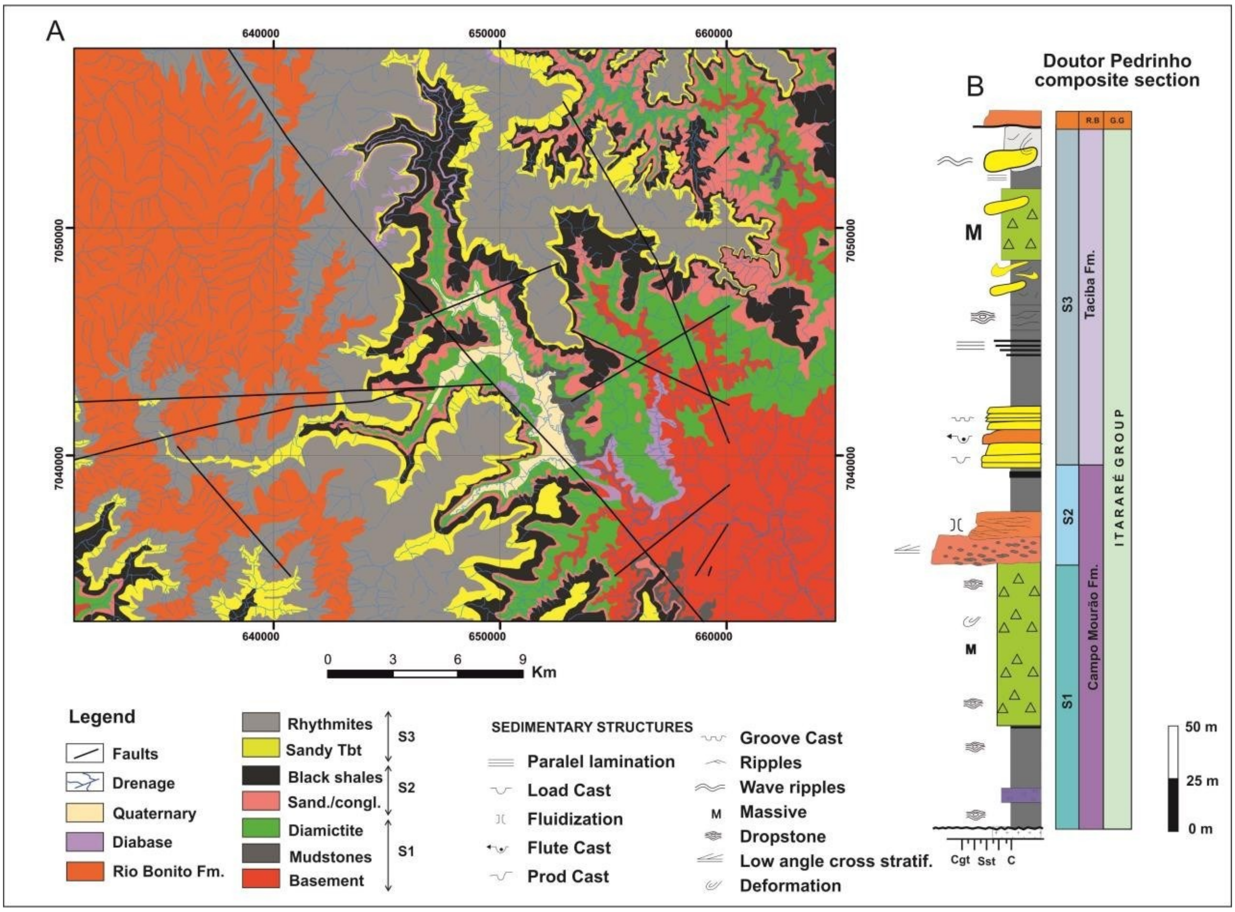

A
640000
650000
660000
7050000
7040000
0 3 6 9 Km
Legend
Faults
Drenage
Quaternary
Diabase
Rio Bonito Fm.
Rhythmites
Sandy Tbt
Black shales
Sand./congl.
Diamictite
Mudstones
Basement
S3
S2
S1
SEDIMENTARY STRUCTURES
Paralel lamination
Load Cast
Fluidization
Flute Cast
Prod Cast
Groove Cast
Ripples
Wave ripples
Massive
Dropstone
Low angle cross stratif.
Deformation
B
Doutor Pedrinho composite section
M
Cgt Sst C
Taciba Fm.
Campo Mourão Fm.
ITARARÉ GROUP
R.B
G.G
50 m
25 m
0 m

Figure 3

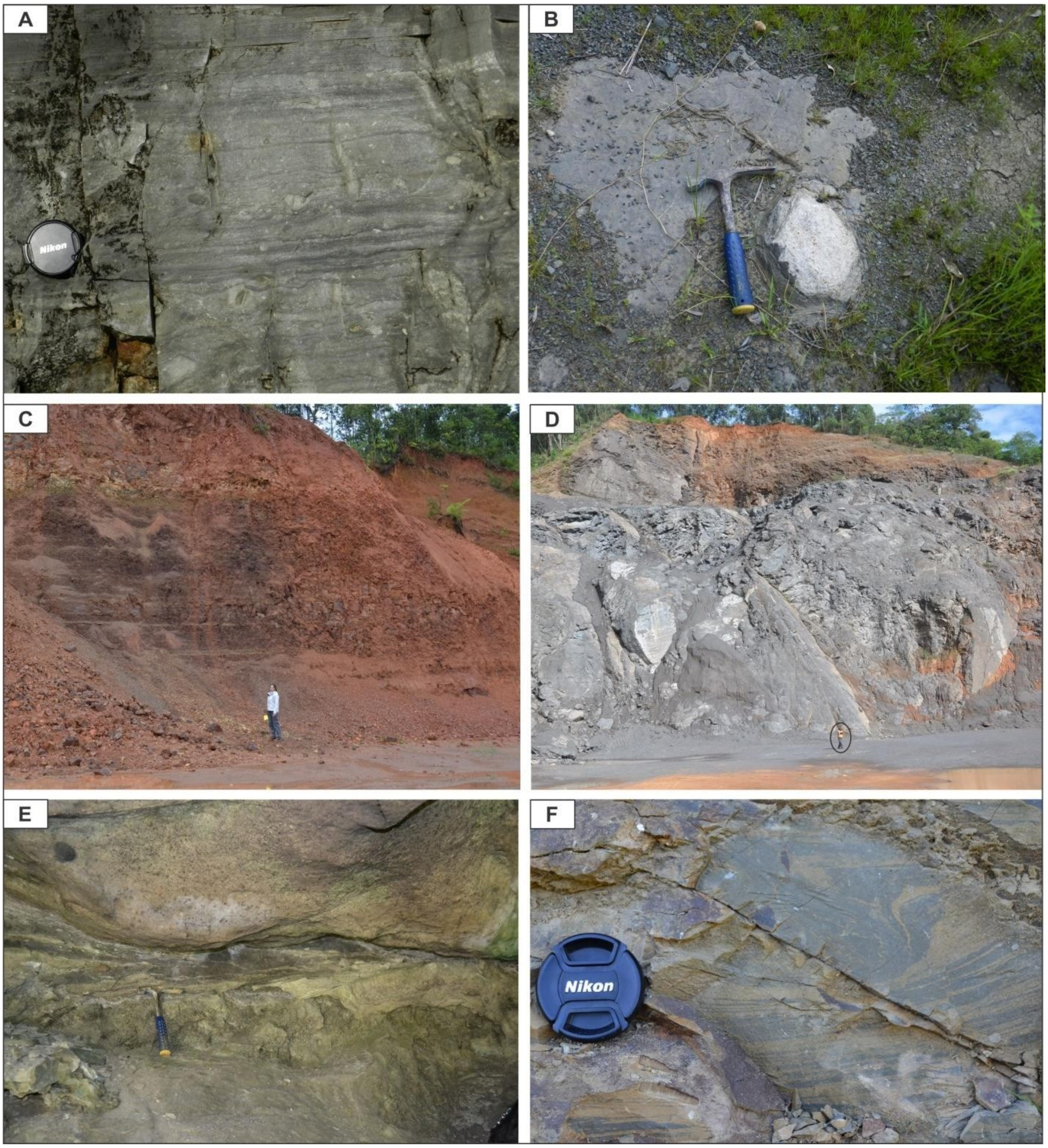


Figure 4

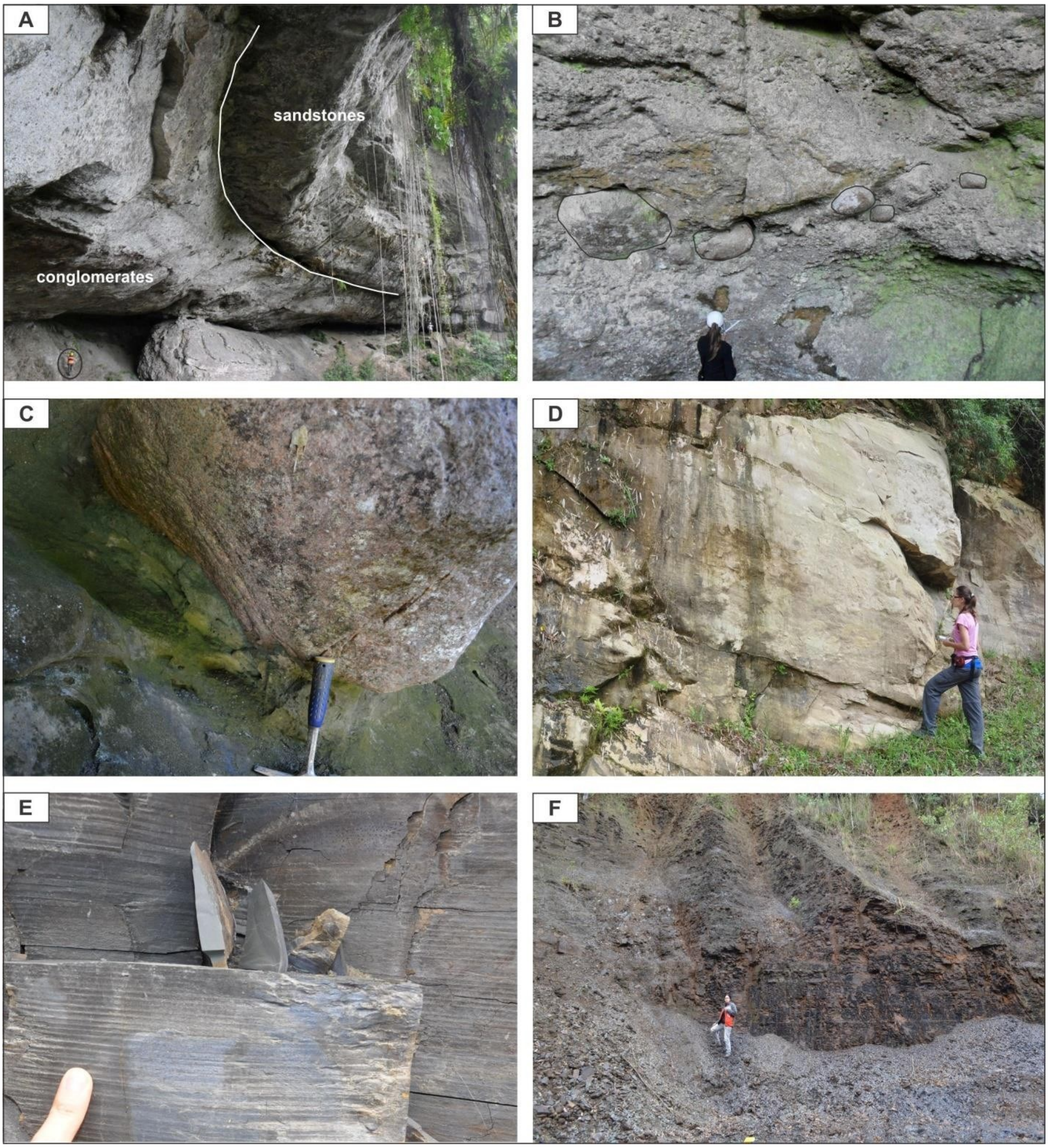


Figure 5

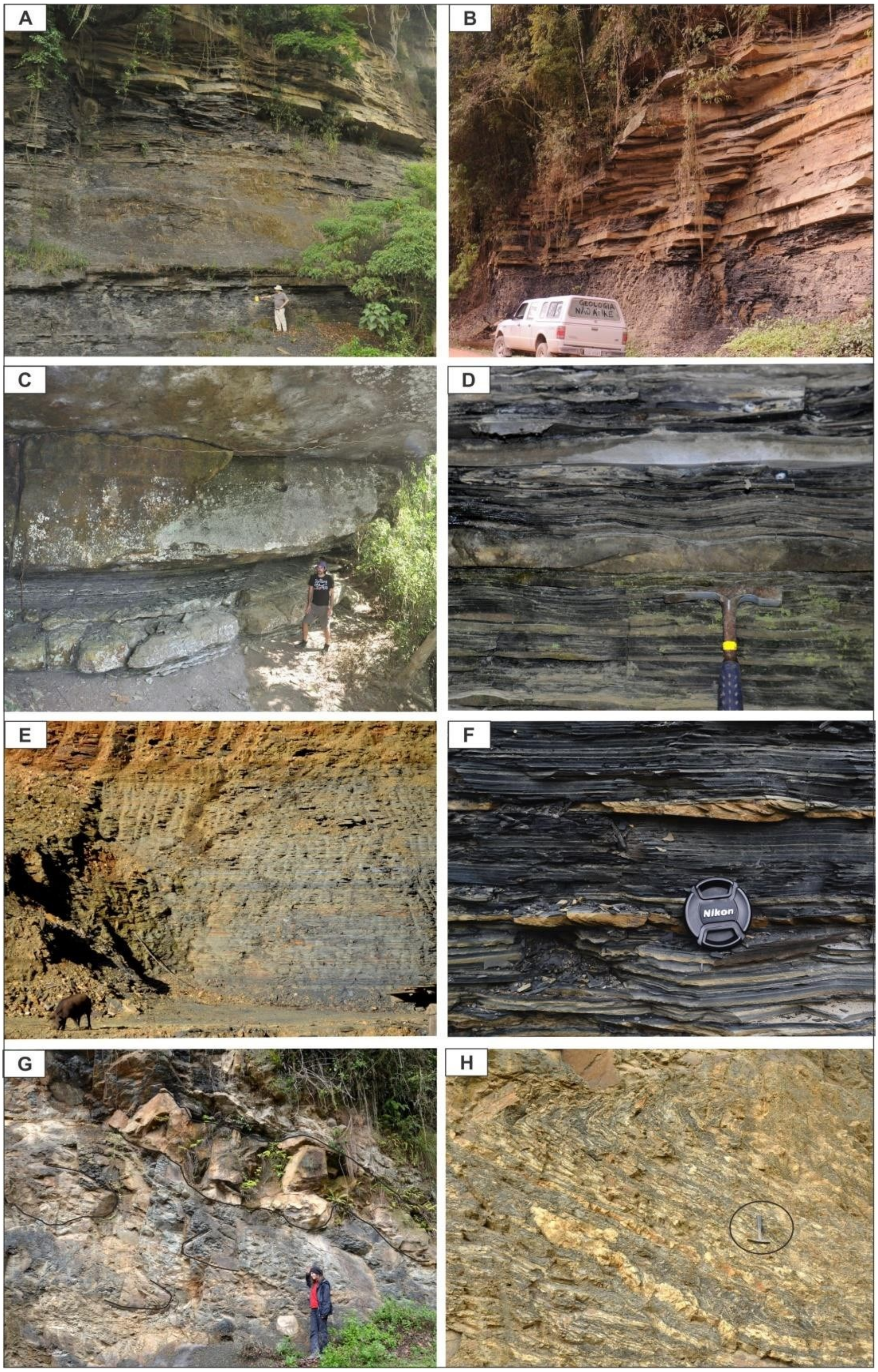


Figure 6

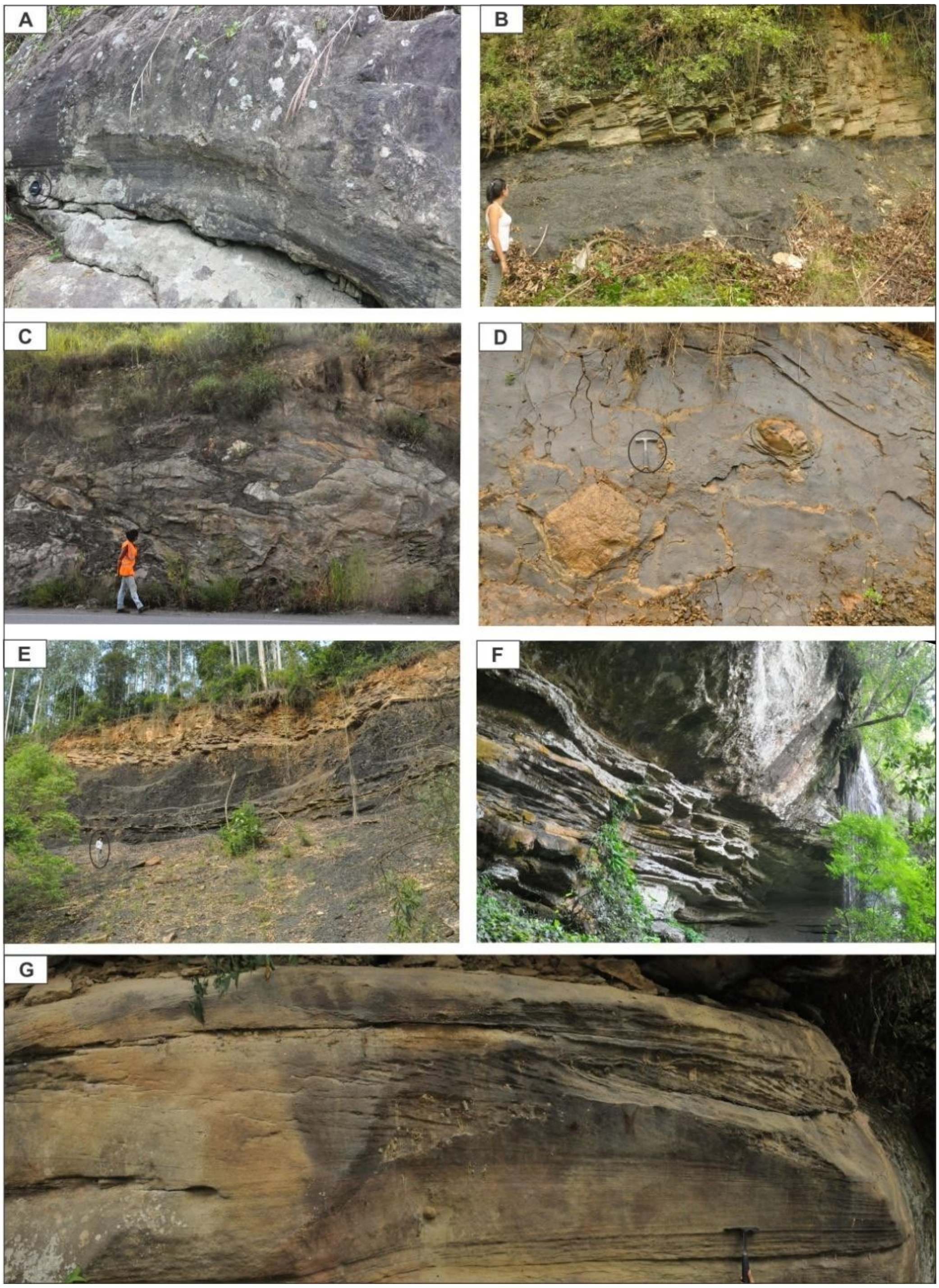
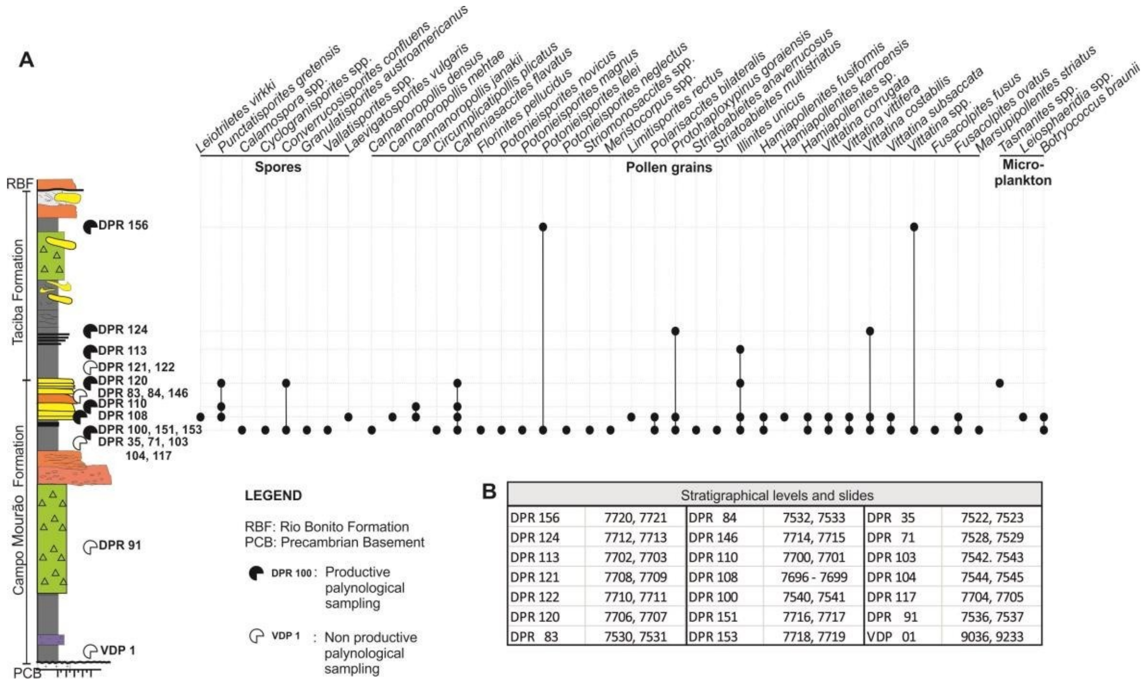
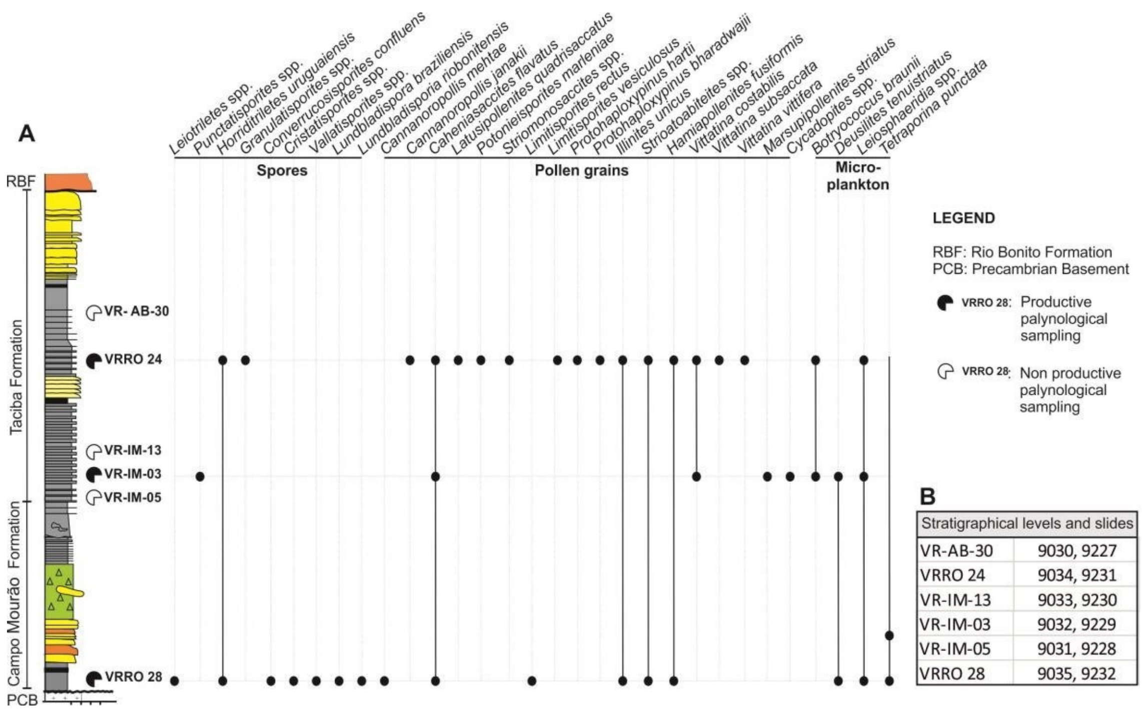


Figure 7



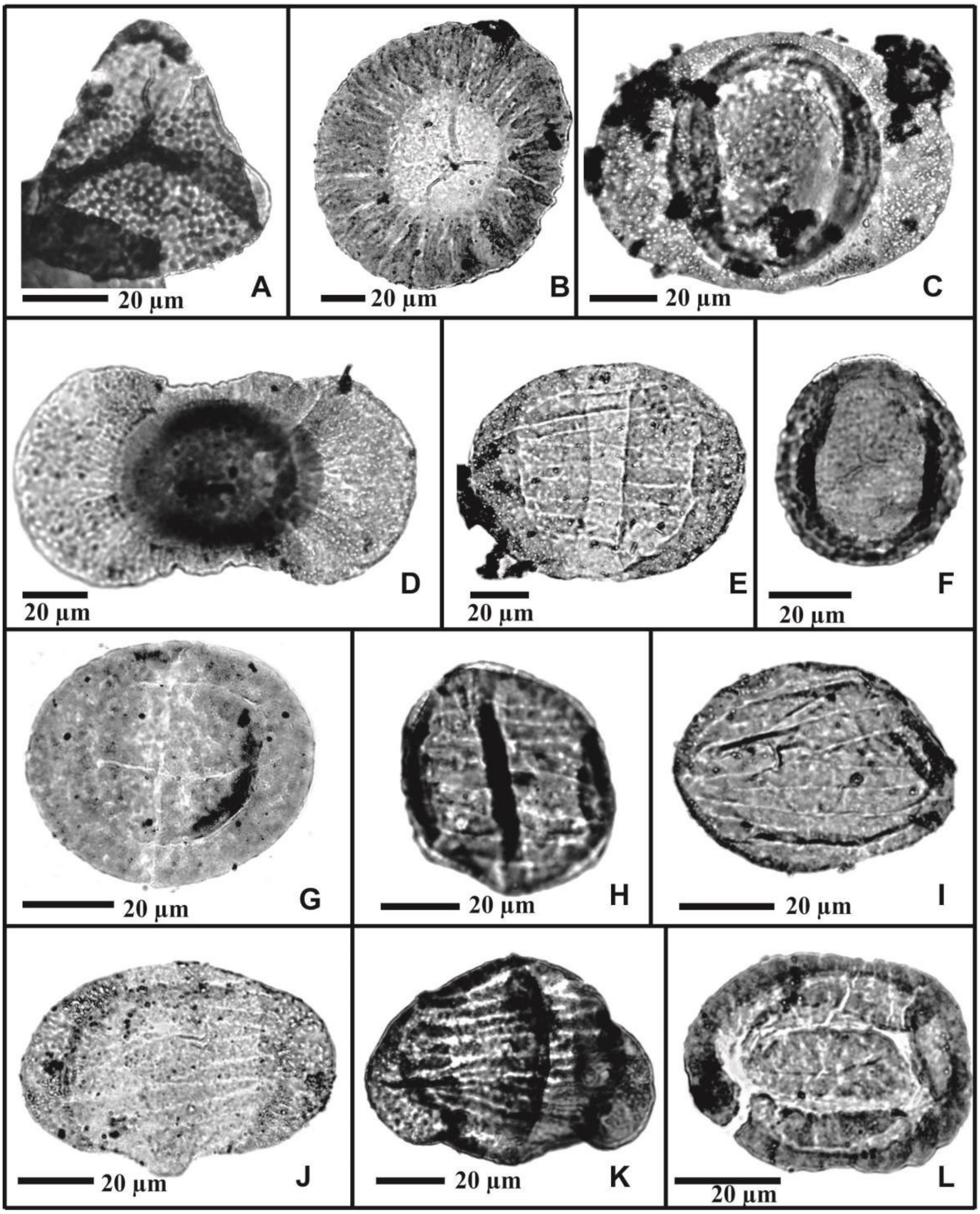
Stratigraphical levels and slides					
DPR 156	7720, 7721	DPR 84	7532, 7533	DPR 35	7522, 7523
DPR 124	7712, 7713	DPR 146	7714, 7715	DPR 71	7528, 7529
DPR 113	7702, 7703	DPR 110	7700, 7701	DPR 103	7542. 7543
DPR 121	7708, 7709	DPR 108	7696 - 7699	DPR 104	7544, 7545
DPR 122	7710, 7711	DPR 100	7540, 7541	DPR 117	7704, 7705
DPR 120	7706, 7707	DPR 151	7716, 7717	DPR 91	7536, 7537
DPR 83	7530, 7531	DPR 153	7718, 7719	VDP 01	9036, 9233

Figure 8



Stratigraphical levels and slides	
VR-AB-30	9030, 9227
VRRO 24	9034, 9231
VR-IM-13	9033, 9230
VR-IM-03	9032, 9229
VR-IM-05	9031, 9228
VRRO 28	9035, 9232

Figure 9


20 µm
A
20 µm
B
20 µm
C
20 µm
D
20 µm
E
20 µm
F
20 µm
G
20 µm
H
20 µm
I
20 µm
J
20 µm
K
20 µm
L
Figure 10

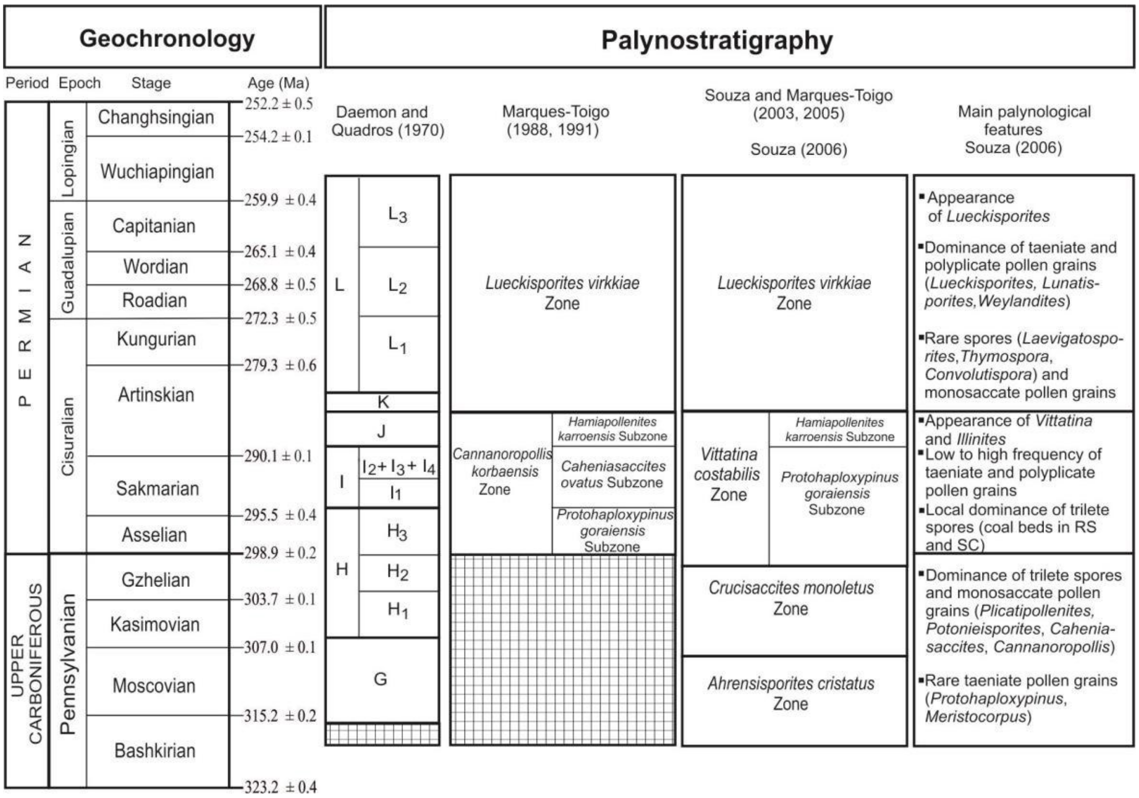


Figure 11

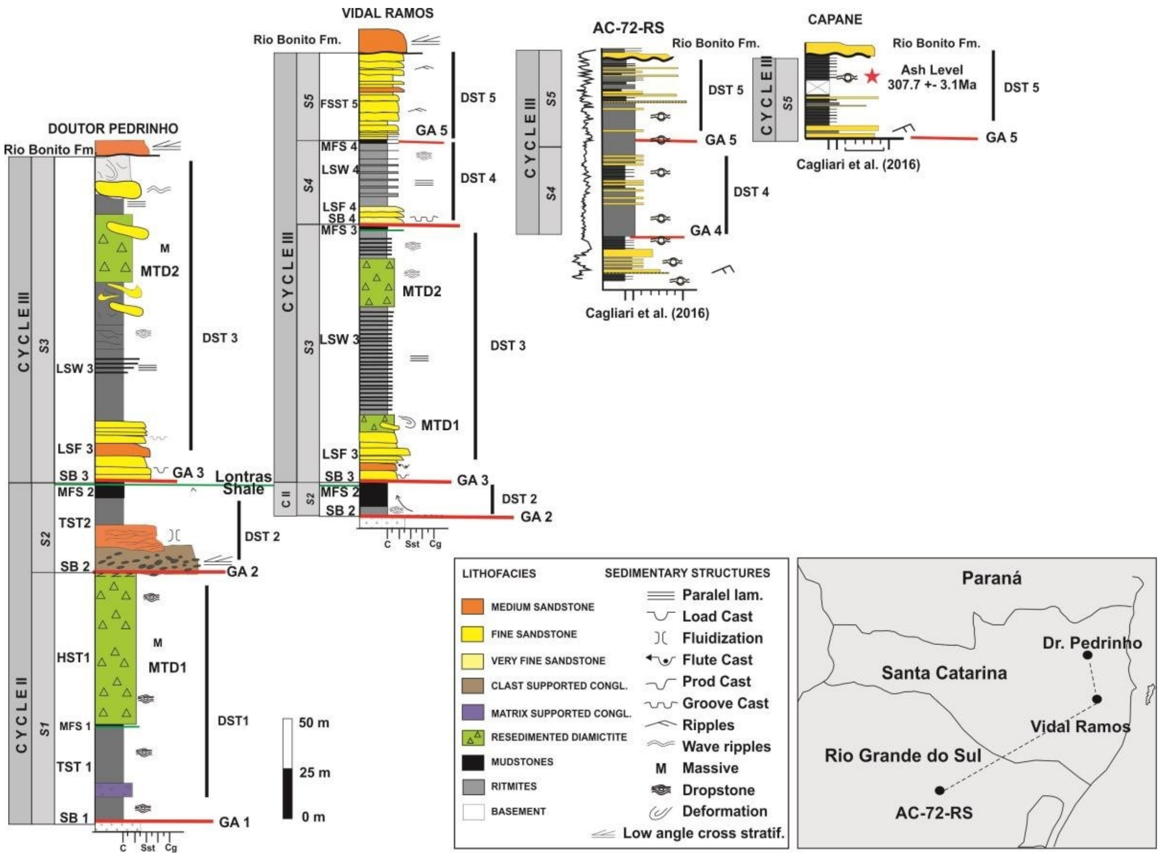


Figure 12

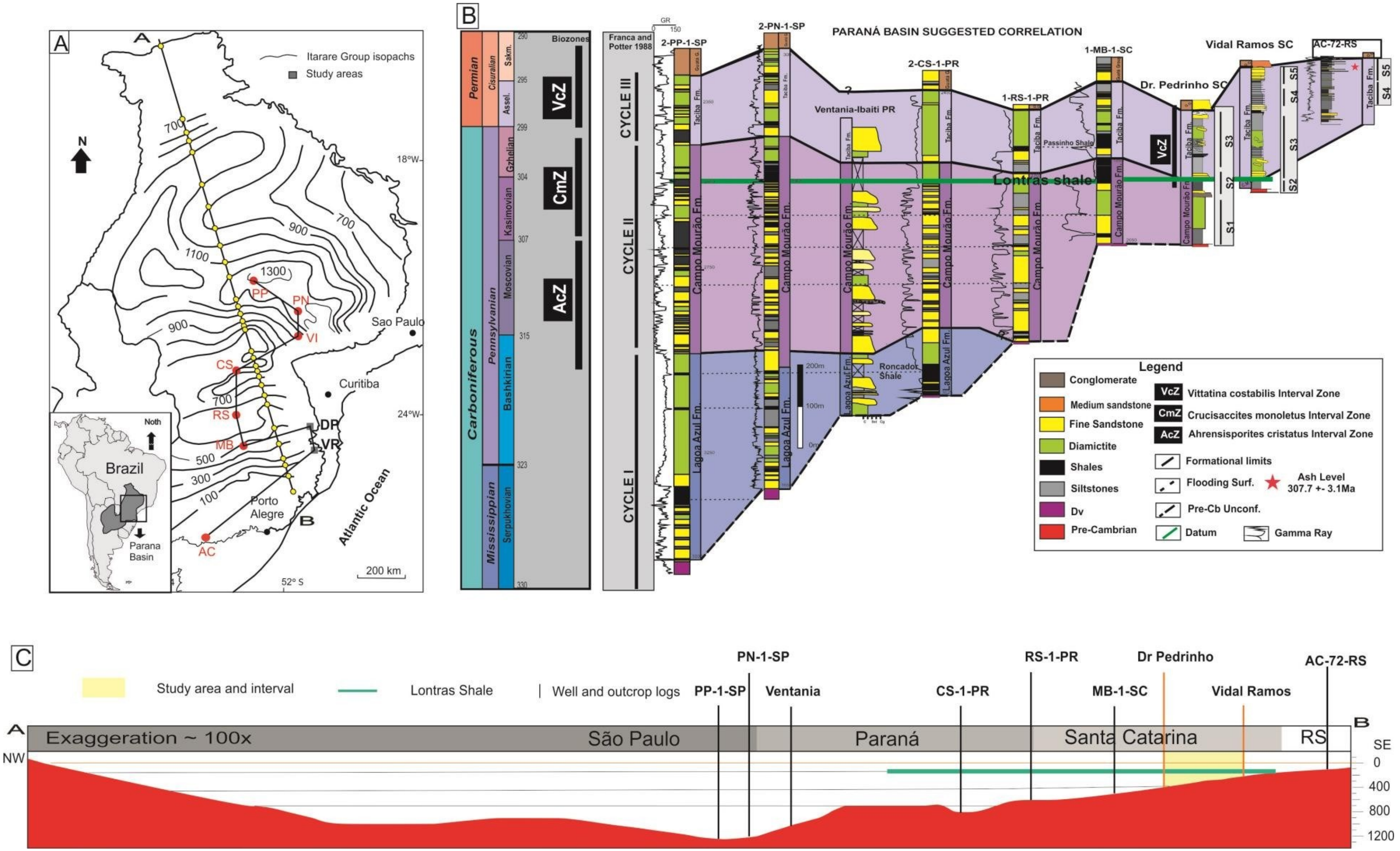

A
Itarare Group isopachs
Study areas
Brazil
Parana Basin
Sao Paulo
Curitiba
Porto Alegre
Atlantic Ocean
200 km
B
PARANÁ BASIN SUGGESTED CORRELATION
Lontras shale
Legend
Conglomerate
Medium sandstone
Fine Sandstone
Diamictite
Shales
Siltstones
Dv
Pre-Cambrian
Vittatina costabilis Interval Zone
Crucisaccites monoletus Interval Zone
Ahrensisporites cristatus Interval Zone
Formational limits
Flooding Surf.
Pre-Cb Unconf.
Datum
Gamma Ray
Ash Level 307.7 +- 3.1Ma
C
Study area and interval
Lontras Shale
Well and outcrop logs
Exaggeration ~ 100x
São Paulo
Paraná
Santa Catarina
RS

Figure 13

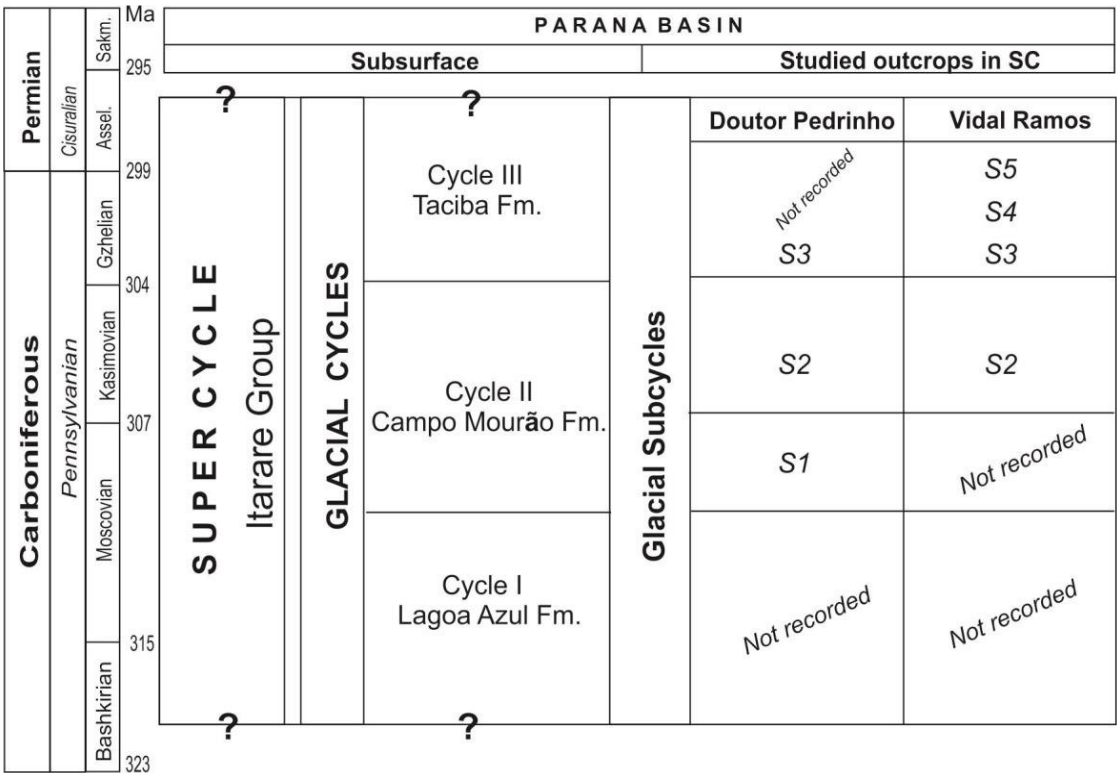

Ma
PARANA BASIN
Subsurface
Studied outcrops in SC
Permian
Carboniferous
Cisuralian
Pennsylvanian
Sakm.
Assel.
Gzhelian
Kasimovian
Moscovian
Bashkirian
295
299
304
307
315
323
SUPER CYCLE
Itarare Group
GLACIAL CYCLES
Cycle III
Taciba Fm.
Cycle II
Campo Mourão Fm.
Cycle I
Lagoa Azul Fm.
Glacial Subcycles
Doutor Pedrinho
Vidal Ramos
Not recorded
S3
S5
S4
S3
S2
S2
S1
Not recorded
Not recorded
Not recorded
?
?
?
?

Figure 14

HIGHLIGHTS

Late Palaeozoic glacial cycles in western Gondwana

Correlation of long and short-term glacial cycles

Palynology of the upper Itararé group

Sequence stratigraphy of glacially-related successions